Physics of B_s^0 Mesons and Bottom Baryons

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Abstract. We discuss the physics of B_s^0 mesons focusing on CP violation in $B_s^0 \to J/\psi\phi$ decays at the Tevatron. We summarize measurements of the properties of bottom baryons at the Tevatron including the Σ_b states and the Ξ_b^- baryon. We also discuss the discovery of the Ω_b^- baryon.

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INTRODUCTION

The past decade has seen an overwhelming amount of exciting heavy flavour physics results [1] from the e^+e^- B factory experiments BaBar and Belle as well as the CDF and D0 experiments operating at the Tevatron $p\bar{p}$ collider. In many cases, the measurements performed at the Tevatron Collider are complementary to those at the B factories. In particular, all B hadron states are produced at the Tevatron. Besides the neutral B^0 and the charged B^+ which are the only products at the $\Upsilon(4S)$ resonance, the Tevatron is also a source of B mesons containing s- or c-quark: B_s^0 and B_c^+. In addition, baryons containing bottom quarks such as the Λ_b^0, Ξ_b^-, Σ_b^- or Ω_b^- baryons are produced at the Tevatron.

Why do we study B hadron states? In analogy to the hydrogen atom which consists of a heavy nucleus in form of the proton surrounded by a light electron, a B hadron consists of a heavy bottom quark surrounded either by a light anti-quark, to form a B meson or a di-quark pair, to form a bottom baryon. The interaction between the b quark and the other quark(s) in a B hadron is based on the strong interaction or Quantum Chromodynamics (QCD) while the interaction between proton and electron is based on the electromagnetic Coulomb interaction and described by Quantum Electrodynamics in its ultimate form. Heavy quark hadrons are often called the hydrogen atom of QCD. The study of B hadron states is thus the study of (non-perturbative) QCD, providing sensitive tests of all aspects of QCD, including lattice gauge calculations. In addition, the study of the Cabibbo-Kobayashi-Maskawa (CKM) mechanism which governs quark transitions allows for precision tests of the standard model (SM) and the search for physics beyond the SM through measurements of loop processes in which non-SM particles can contribute.

After a successful 1992-1996 Run I data taking period (for a review of B physics results from e.g. CDF in Run I see Ref. [2]), the Fermilab Tevatron operates in Run II at a centre-of-mass energy of 1.96 TeV with a bunch crossing time of 396 ns generated by 36×36 $p\bar{p}$ bunches. The initial Tevatron luminosity steadily increased from 2002 to 2009 with a present peak luminosity of $35 \cdot 10^{31}$ cm^{-2}s^{-1} reached in 2009. The total integrated luminosity delivered by the Tevatron to CDF and D0 at the time of this conference is ~ 6.5 fb^{-1} with about 5.5 fb^{-1} recorded to tape by each collider experiment. However, most results presented in this review use about 1-4 fb^{-1} of data.

PHYSICS OF B_s^0 MESONS

In the neutral B_s^0 system there exist two flavour eigenstates, the $B_s^0 = |\bar{b}s\rangle$ and $\bar{B}_s^0 = |b\bar{s}\rangle$. The mass eigenstates B_s^H and B_s^L are admixtures of the flavour eigenstates B_s^0 and $\bar{B}_s^0$:

$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle, \qquad |B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle, \quad \text{with } \frac{q}{p} = \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}. \tag{1}$$

The fact that the mass eigenstates are not the same as the flavour states gives rise to oscillations between the B_s^0 and $\bar{B}_s^0$ states with a frequency proportional to the mass difference of the mass eigenstates, $\Delta m_s = m_H - m_L$. In the SM particle-antiparticle oscillations are explained in terms of second-order weak processes involving virtual massive particles that provide a transition amplitude between the B_s^0 and $\bar{B}_s^0$ states. The decay width difference between the mass eigenstates $\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2\,|\Gamma_{12}|\cos\phi_s$ is related to the *CP* phase $\phi_s = \arg(-\mathrm{M}_{12}/\Gamma_{12})$ where M_{12} and Γ_{12} are the off-diagonal elements of the mass and decay matrix. The decay $B_s^0 \to J/\psi\phi$ is the transition of the spin-0 pseudo-scalar B_s^0 into two spin-1 vector particles. The orbital angular momenta of the vector mesons, J/ψ and ϕ, can be used to distinguish the *CP* even *S*-wave ($L = 0$) and *D*-wave ($L = 2$) final states from the *CP* odd *P*-wave ($L = 1$) final state. Such an angular decomposition reveals that the decay is dominated by the *CP* even state.

CP Violation in $B_s^0 \to J/\psi\phi$

In analogy to measurements of the time dependent *CP* asymmetry in neutral B^0 decays into e.g. $B^0 \to J/\psi K_S^0$ accessing the *CP* violating phase $\sin(2\beta)$ which arises through the interference between decay and mixing, the application of flavour tagging to $B_s^0 \to J/\psi\phi$ events measures the corresponding phase in B_s^0 decays. This phase, which is responsible for *CP* violation in $B_s^0 \to J/\psi\phi$ in the standard model, is in analogy to the phase $\sin(2\beta)$ called $\sin(2\beta_s^{SM})$ and is defined through the CKM matrix elements as $\beta_s^{SM} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$. In the context of the SM, this phase is expected to be small ($2\beta_s^{SM} \sim 0.04$) and its measurement is currently beyond the experimental reach of the Tevatron. However, new physics may contribute significantly larger values to the *CP* violating phase in $B_s^0 \to J/\psi\phi$ decays [3, 4, 5]. In this case, the observed *CP* phase would be modified by a phase ϕ_s^{NP} due to new physics processes, and can be expressed as $2\beta_s^{J/\psi\phi} = 2\beta_s^{SM} - \phi_s^{NP}$. The current interest in measuring *CP* violation in $B_s^0 \to J/\psi\phi$ is therefore in searching for enhanced *CP* violation through new physics processes.

At the time of this conference, both Tevatron experiments have presented tagged, time dependent angular analyses of $B_s^0 \to J/\psi\phi$ decays. Due to the non-parabolic behaviour of the log-likelihood function, no meaningful point estimates for $\beta_s^{J/\psi\phi}$ can be quoted and both experiments construct their results as confidence level regions in the plane of $\Delta\Gamma_s$ versus $\beta_s^{J/\psi\phi}$. The D0 result [6] based on 2.8 fb^{-1} of data is shown in Figure 1(a) while a published result from CDF based on 1.35 fb^{-1} of data [7] exists. A preliminary update from CDF with 2.8 fb^{-1} of data is displayed in Figure 1(b). Both experiments observe a mild inconsistency with the SM prediction $2\beta_s^{SM} \sim 0.04$.

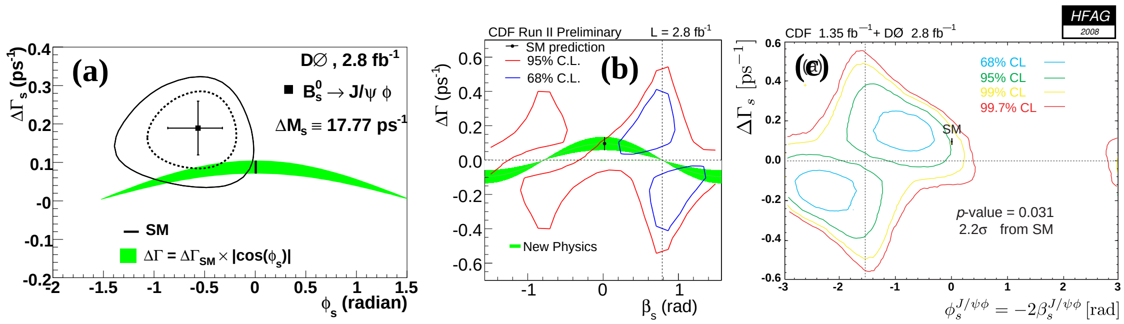

FIGURE 1. Confidence level regions in plane of $\Delta\Gamma_s$ versus $\beta_s^{J/\psi\phi}$ in flavour-tagged $B_s^0 \to J/\psi\phi$ analysis from (a) the 2.8 fb^{-1} result from D0, (b) the preliminary 2.8 fb^{-1} result from CDF and (c) the combination of CDF and D0 likelihoods. Note the transformation $2\beta_s^{J/\psi\phi} = -\phi_s^{J/\psi\phi}$.

Interestingly, the CDF and D0 inconsistencies with the standard model both point in the same direction. Assuming the SM prediction, CDF quotes a probability of 7% to observe a likelihood ratio equal or higher than the one observed in data which corresponds to about $1.8\,\sigma$. Using constraints on the strong phases, D0 finds a p-value of 6.6% corresponding to a $1.8\,\sigma$ inconsistency with the SM hypothesis [6]. The combination of the results from Refs. [6] and [7] is shown in Figure 1(c), restricting $\beta_s^{J/\psi\phi}$ to the interval $[0.14, 0.73] \cup [0.83, 1.42]$ at 90% confidence level. The consistency of the combined result with the SM gives a p-value of 3.1% corresponding to a $2.2\,\sigma$ discrepancy with the SM prediction.

PHYSICS OF BOTTOM BARYONS

Until 2006 only one bottom baryon, the Λ_b^0, had been directly observed. The $\Sigma_b^{(*)}$ baryon states with quark content $\Sigma_b^{(*)+} = |buu\rangle$ and $\Sigma_b^{(*)-} = |bdd\rangle$ have been discovered by CDF [8] in 2007 through their strong decay $\Sigma_b^{(*)\pm} \to \Lambda_b^0\pi^\pm$ using fully reconstructed $\Lambda_b^0 \to \Lambda_c^+\pi^-$ candidates. The Ξ_b^- baryon with a quark content of $\Xi_b^- = |bds\rangle$ was observed by CDF and D0 in the mode $\Xi_b^- \to J/\psi\Xi^-$ followed by $\Xi^- \to \Lambda\pi^-$ with $\Lambda \to p\pi^-$ and $J/\psi \to \mu^+\mu^-$. The D0 analysis [9] based on 1.3 fb^{-1} of data finds $(15.2 \pm 4.4^{+1.9}_{-0.4})$ Ξ_b^- signal event with a Gaussian significance of $5.2\,\sigma$ as shown in Figure 2(a). D0 reports a mass of $m(\Xi_b^-) = (5774 \pm 11 \pm 15)$ MeV$/c^2$. CDF observes (17.5 ± 4.3) Ξ_b^- signal events [10] with a Gaussian significance of $7.7\,\sigma$ and measures a Ξ_b^- mass of $m(\Xi_b^-) = (5792.9 \pm 2.5 \pm 1.7)$ MeV$/c^2$.

Observation of the Ω_b^- Baryon

In August 2008, the D0 collaboration announced the observation of another heavy bottom baryon [11], the double strange Ω_b^- baryon with quark content $|bss\rangle$. Building on the previous observation of the Ξ_b^-, D0 reconstructs $\Omega_b^- \to J/\psi\Omega^-$ followed by

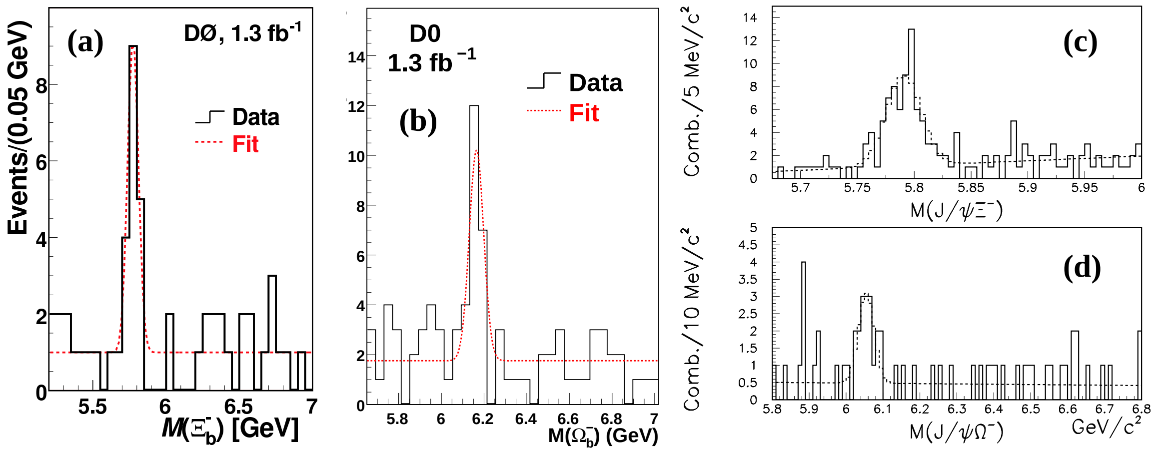

FIGURE 2. Invariant mass distributions of (a) Ξ_b^- and (b) Ω_b^- from D0, (c) Ξ_b^- and (d) Ω_b^- from CDF.

$\Omega^- \to \Lambda K^-$ in the same dataset using 1.3 fb^{-1} of $p\bar{p}$ collisions. A mass measurement of $m(\Omega_b^-) = (6165 \pm 10 \pm 13)$ MeV$/c^2$ is reported based on an Ω_b^- signal of $(17.8 \pm 4.9 \pm 0.8)$ events shown in Figure 2(b). The significance of the observed signal is $5.4\,\sigma$ corresponding to a probability of 6.7×10^{-8} of it arising from background fluctuation. D0 measures the Ω_b^- rate with respect to Ξ_b^- production to be $0.80 \pm 0.32^{+0.14}_{-0.22}$.

In May 2009, CDF released a comprehensive reconstruction of bottom baryons with a J/ψ in the final state [12]: $\Lambda_b^0 \to J/\psi\Lambda$, $\Xi_b^- \to J/\psi\Xi^-$ and $\Omega_b^- \to J/\psi\Omega^-$. CDF reconstructs (66^{+14}_{-9}) Ξ_b^- and (16^{+6}_{-4}) Ω_b^- candidates shown in Fig. 2(c) and (d), respectively. A $5.5\,\sigma$ significance for an Ω_b^- observation is reported together with mass measurements of $m(\Xi_b^-) = (5790.9 \pm 2.6 \pm 0.9)$ MeV$/c^2$ and $m(\Omega_b^-) = (6054.4 \pm 6.8 \pm 0.9)$ MeV$/c^2$ in good agreement with theoretical predictions for the Ω_b^- mass. While there is agreement between the Ξ_b^- mass measurements, a significant mass difference of $(111 \pm 12 \pm 14)$ MeV$/c^2$ exists between the Ω_b^- masses reported by CDF and D0. CDF normalizes the observed Ω_b^- and Ξ_b^- rates to its Λ_b^0 production where both ratios correspond to a Ω_b^- rate of $0.27 \pm 0.12 \pm 0.01$ normalized to Ξ_b^- production.

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